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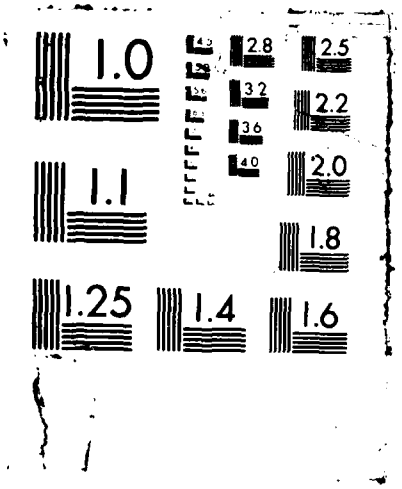
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Z. C. Wu, Daniel A. Jelski and Thomas F. George

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This paper discusses the behavior of currents and fields along a structured superconductor. First the effect of surface structure on supercurrents is investigated. Then the effect of structure on the critical nucleation field is discussed in two cases, one with the magnetic field parallel to the ripples and the other with the field parallel to the grating wavenumber. In the first case, it is found that the critical field is reduced as a function of grating height, whereas in the latter case it is increased. Finally, the relevance of this work for laser-induced chemistry above a superconducting surface is discussed. The Ginzburg-Landau model is used throughout.

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SUPERCONDUCTORS WITH STRUCTURED SURFACES: FIELDS AND CURRENTS

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ABSTRACT

This paper discusses the behavior of currents and fields along a structured superconductor. First the effect of surface structure on supercurrents is investigated. Then the effect of structure on the critical nucleation field is discussed in two cases, one with the magnetic field parallel to the ripples and the other with the field parallel to the grating wavenumber. In the first case, it is found that the critical field is reduced as a function of grating height, whereas in the latter case it is increased. Finally, the relevance of this work for laser-induced chemistry above a superconducting surface is discussed. The Ginzburg-Landau model is used throughout.

A-1

INTRODUCTION

The enormous recent interest in superconductivity [1] is no longer worthy of remark. In this paper, we shall not discuss the fundamental theory behind the phenomenon, nor shall we consider the specific structure of any given material. Instead, we shall investigate a generic superconducting material along the surface of which is inscribed a sinusoidal grating. We are ultimately interested in investigating the optical properties of thin films, which we suppose have microscopic roughness on the surface. While we are not yet able to treat the time-dependent problem satisfactorily, we shall discuss the response of the rippled surface to external fields. We wish to use the Ginzburg-Landau theory [2] to analyze the effect of the grating amplitude on the current, the superelectron density and, most importantly, on the critical nucleation field. The reason for doing this is to get a better idea of how a thin-film superconductor will respond to external fields. While we are at present restricted to static fields (the Ginzburg-Landau theory is not time dependent), we suppose the result to be valid in the low-frequency domain. We hope, eventually, to develop an explicit time-dependent model.

The Ginzburg-Landau (GL) model is very appropriate here. Its validity is largely independent of the microscopic causes of superconductivity, the microscopic theory being used only to evaluate necessary parameters. Further, it is an expansion in terms of the order parameter, the superelectron density, which may be expected to go to zero at the critical temperature. Hence the limiting condition is not what the critical temperature is, nor what the microscopic causes are, but simply that the temperature be close to T_c. Thus we expect our current results to apply equally to the new high-T_c ceramic materials as to more traditional substances.

In the next section, we shall discuss the effect of the grating amplitude on the supercurrent. Then we shall consider the critical nucleation field for two cases: the magnetic field parallel to the wavenumber (x-direction) and parallel to the

ripples (y-direction). We shall find that the critical field is reduced in the first case, while it is increased in the second. Finally, we shall consider some implications of this work for optics and chemistry above superconducting surfaces.

ELECTRON DENSITY AND SUPERCURRENTS

The behavior of the GL equation near a flat surface has been discussed by de Gennes [3]. We have extended this result to allow for a rippled surface [4] by solving a two-dimensional elliptic equation rather than the one-dimensional harmonic equation. A more detailed discussion appears in that reference. A problem arises in choosing the proper boundary conditions. The appropriate boundary condition for the GL equation at a surface is

$$\left(\frac{\hbar}{2}\vec{\nabla} - \frac{e^*}{c}\vec{A}\right)\psi\Big|_n = \frac{i}{b}\psi \quad . \qquad (1)$$

This condition can be satisfied in at least two ways. We can impose Dirichlet boundary conditions, where we set $b = 0$, which implies $\psi = 0$, or we can impose von Neumann boundary conditions, where $b = \infty$. The electron density function is, of course, strongly dependent on which boundary conditions one chooses. Figures 1 and 2 illustrate the differences. Figure 1 shows the effect of the Dirichlet conditions at the ripples. Here the density is sharply reduced in the "fingers". Conversely, the density calculated from imposing von Neumann conditions is shown in Fig. 2. Here the derivative of the wavefunction is zero across the boundary. Note that the greatest electron density is just below the ripples.

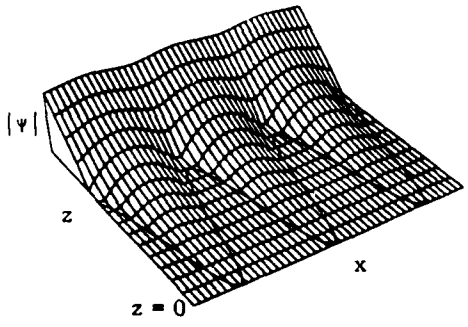

Figure 1
The electron density near a rippled surface given Dirichlet boundary conditions. See Ref. 4 for details. The z-coordinate denotes the normal distance from the surface into the interior of the material.

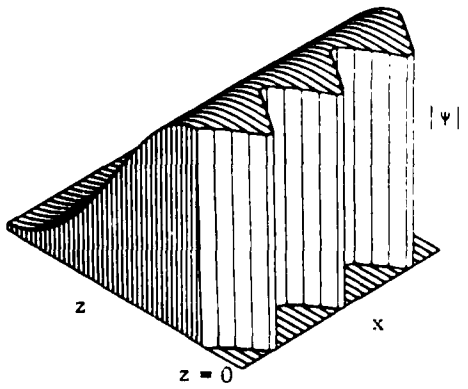

Figure 2
The electron density near a rippled surface given von Neumann boundary conditions. See Ref. 6 for details.

Let us now restrict our attention to the Dirichlet problem, and this for the following reason. We are using the linearized GL equation to solve the problem. The linear equation is valid as long as ψ is much smaller than ψ_∞, where $|\psi_\infty|^2$ is the bulk value of the superelectron density. There are at least two ways in which this approximation can be made valid. One is when we are near the surface and the Dirichlet conditions hold, and the other is for an external field very near the critical field. Since we are presently considering currents, and not fields, we are thus restricted by the linear approximation to the Dirichlet condition. DeGennes has shown from an analysis based on the microscopic theory (BCS) that superconductors in zero field obey the Dirichlet conditions. In subsequent sections we shall consider the high field case where the von Neumann conditions are appropriate.

It has been found [4] that ripples increase the current path length. The ripples create vortices in the current flow. However, it has also been discovered that the ripples provide essentially the same Meissner-effect shielding as a "bulk" surface would. Hence, if the goal is to maximize current flow, then as flat a surface as possible is desirable. Conversely, if the purpose is to provide a constant current impervious to small changes in the external field, then the ripples are desirable.

CRITICAL NUCLEATION FIELD PARALLEL TO GRATING WAVENUMBER

It is interesting to calculate the critical field at which superconductivity can nucleate near a surface in a decreasing magnetic field, H_{c3}. At this critical field, the superelectron density must be infinitesimal and the linearized version of the GL equations becomes accurate. The analogous nucleation problem for the bulk material, or near a flat surface, has been solved by deGennes and Saint-James [3,5]. It is found that H_{c3} for a flat surface is $1.695 \cdot H_{c2}$, where H_{c2} is the critical field for the bulk.

We have investigated the critical nucleation field for a superconducting surface with a sinusoidal grating [6]. In this case, two mutually perpendicular directions along the surface must be distinguished. In this section, we shall consider the field to be parallel to the grating wavenumber, which we shall consider to be the x-direction. Then translational symmetry along this axis disappears, and the GL equation becomes two-dimensional. We use the von Neumann boundary conditions for the nucleation problem since we are interested in the superelectron density at the surface, precluded under the Dirichlet conditions. The problem is to find the maximum field under which the GL equation has a bound solution, i.e., the wavefunction must decay exponentially into the interior of the material. This equation must be solved numerically. There is a further parameter, namely the supercurrent density in the y-direction (parallel to the ripple), and this is chosen variationally to minimize the eigenvalue, which corresponds to maximum field.

Under these circumstances, it is found that the critical field decreases as a function of grating amplitude (Fig. 3). In the limit of infinitely large amplitude, it is found that the nucleation field approaches that of the bulk limit, which is to be expected from an analysis of a series of parallel thin films.

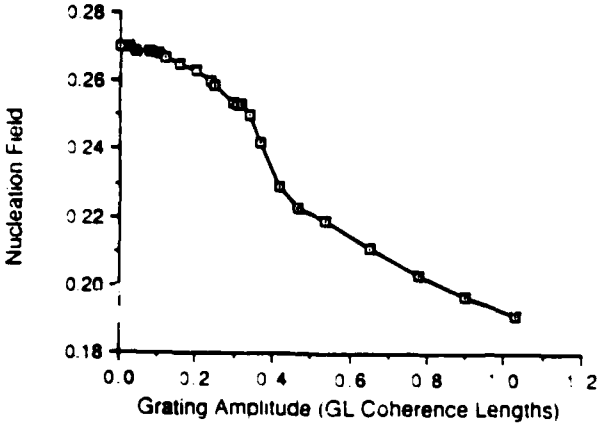

Figure 3
Nucleation critical field vs. grating amplitude for a field oriented parallel to the grating wavenumber. See Ref. 6 for details. The unit for the field is $2\pi m^* c|\alpha|/\hbar e$.

CRITICAL NUCLEATION FIELD PARALLEL TO THE RIPPLE

Another interesting case we now consider is the nucleation field in the ripple direction (y-direction). The gauge for the vector potential is

$$\vec{A} = (H_y z,\ 0,\ 0) \quad .$$

The GL equation can be written as

$$-\frac{\partial^2 f(x,z)}{\partial x^2} - \frac{\partial^2 f(x,z)}{\partial z^2} + \frac{4\pi i H_y z}{\Phi_0}\frac{\partial f(x,z)}{\partial x^2} + \left(\frac{2\pi H_y z}{\Phi_0}\right)^2 f(x,z) = -\frac{2m^*\alpha}{\hbar^2} f(x,z) \quad , \tag{2}$$

where

$$\Phi_0 = \frac{hc}{2e} \quad ,$$

and we have used the ansatz

$$\psi = e^{ik_y y} f(x,z),$$

due to translational symmetry along the y-axis. Equation (2) must be supplemented by the von Neumann boundary conditions at the surface, given by Eq. (1) with $b = \infty$. The critical field must be the maximum H_x at which one can find a bound solution, i.e., the wavefunction must decay exponentially into the bulk. There we set the boundary condition so that the magnitude of the wave-function must be constant at constant z. The phase of the wavefunction, at this bottom boundary, is a variational parameter, chosen to maximize the nucleation field. Unlike the previous case, our calculation shows that the critical field increases as a function of grating amplitude (Fig. 4). Here we have used units such that $H_x/\Phi_0 = 1$. It is expected that the value of the critical field will reach the value for superconducting films, with a thickness of the same order as the period of the structure. It is noted that if the thickness of a film is much smaller than the GL coherence length, the critical field must be much greater than the bulk value.

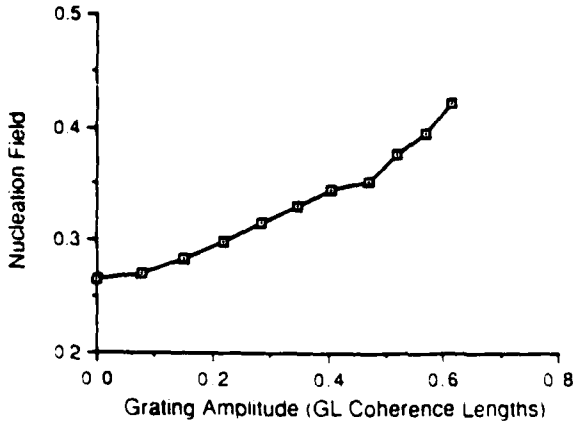

Figure 4
Nucleation critical field vs. grating amplitude for a field oriented parallel to the ripples. The units are the same as for Fig. 3.

CONCLUSIONS

We have considered the behavior of a Ginzburg-Landau superconductor as a function of grating amplitude. We have discussed the two types of problems for which the linearized GL theory is relevant. These are the current density when Dirichlet conditions apply, and the critical nucleation field when von Neumann conditions apply. In subsequent work, we hope to remove the linear condition (i.e. find a quick way of solving the nonlinear equation), and we would also like to remove the condition of static fields.

We have found that if the magnetic field is oriented in a direction parallel to the ripples, then the nucleation field is increased. Conversely, if the field is oriented in the direction of the wavenumber, then the nucleation field is decreased. It follows that if an incident laser of frequency well below the gap frequency is p-polarized with respect to the surface, the intensity of the laser could be stronger than would otherwise be possible, and still not destroy the existence of the superconducting phase along the surface. Similarly, if the laser is s-polarized, the surface nucleation field reduces to that of the bulk in the large amplitude limit.

This research forms the first step in elucidating the behavior of a superconducting surface under laser irradiation. In order to finish this project, it will be necessary to consider the frequency dependence of the GL equations, and also to consider the relation between the superconducting electrons, the normal electrons, and the resulting dielectric constant of the material. Given this information, it will be very interesting to calculate such observables as the reflectivity of a superconducting grating, to consider the existence or non-existence of plasmon waves along the surface, or to evaluate the response of a molecular dipole above the surface.

We close with a few words about the validity of GL theory when applied to the new high T_c superconductors. It appears that the Pippard coherence length of the ceramics is on the order of 4Å, which is much too short to make the present calculation worthwhile. However, the GL coherence length is a function of temperature and increases as the temperature approaches the critical value, although as the temperature comes very near the critical value, fluctuation effects will dominate and invalidate our calculation. Thus we suppose that for higher temperatures, above liquid nitrogen, some of the calculated results here should be observable. In paticular, the qualitative variation of the behavior of the critical field depending on orientation should be measurable.

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